# High Peak Power Lasers and Laser Safety at the BELLA Laser Plasma Accelerator (LPA) Center

**Csaba Tóth** for the BELLA Teams,

*BELLA Center*
*Director: Wim Leemans*

ATAP
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

*Accelerator Safety Workshop – ASW'16*
*September 19 – 22, 2016, Fermilab, IL, USA*

# BELLA Center LPA Facilities

## BELLA Center LPA Facility's mission

- Research platform for Laser Plasma Accelerator science
  (LPAs for electrons, protons, ions and secondary radiation sources)

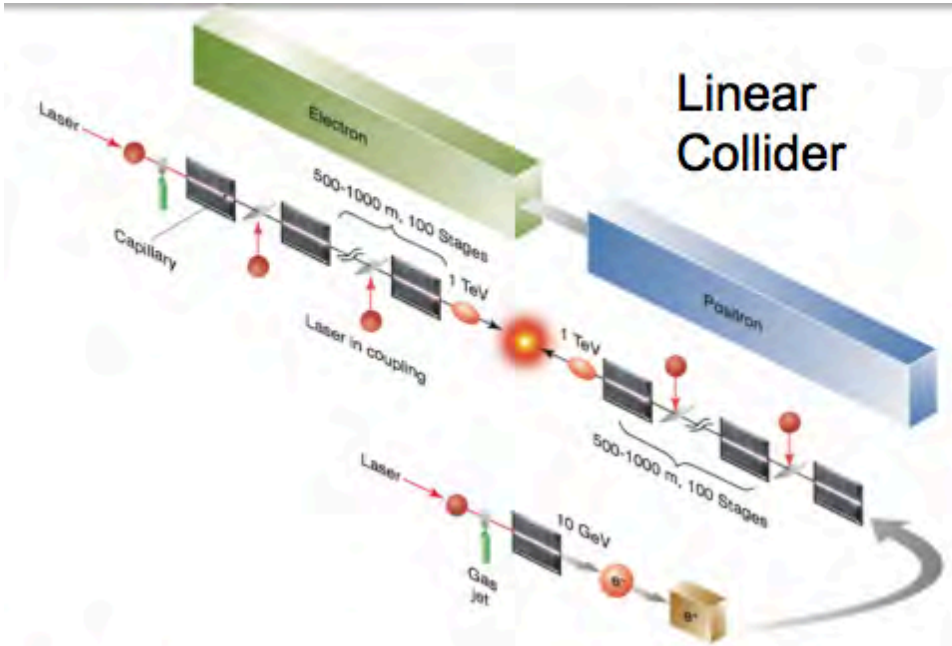
## BELLA Laser systems – past, present, and future

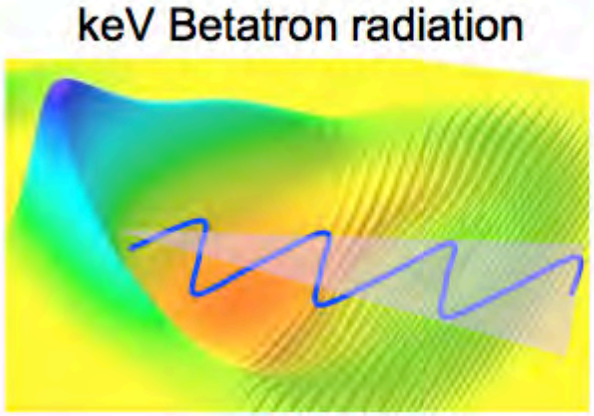
- Design and key operational parameters
- Target systems, controls
- Diagnostics of laser and particle beams

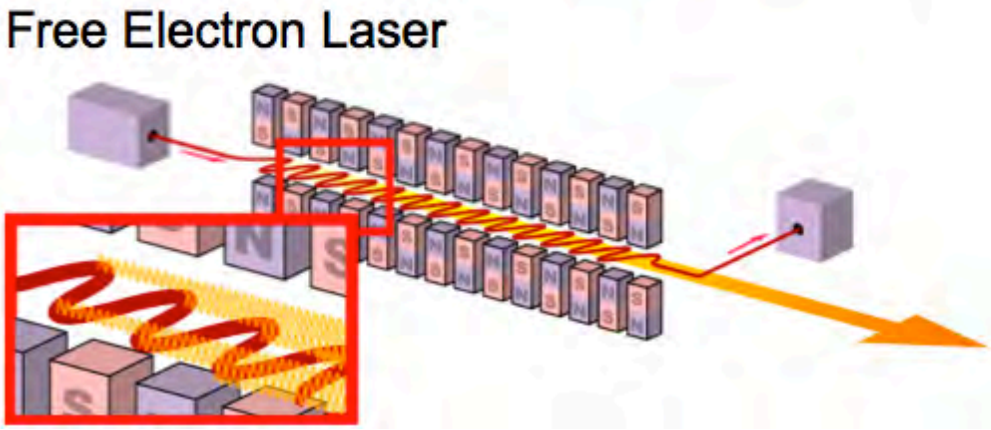
## Challenges in Transition to a Collaborative Research Facility

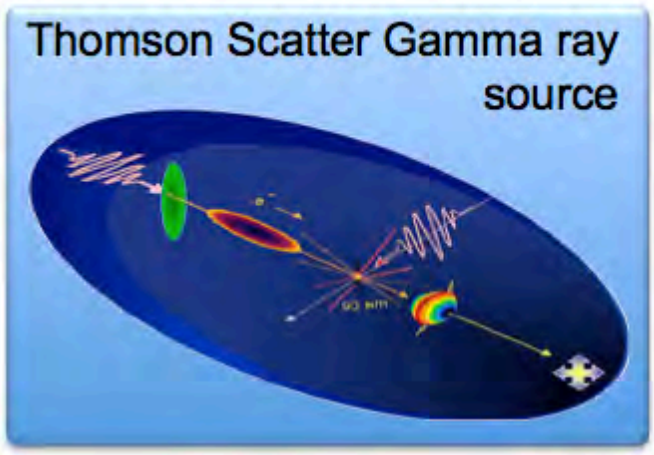
- Configuration control while upgrading existing beamlines ➔ toward new, short focal length beamlines and new targets, new interactions both for $e^-$-s and ions
- Operational experience and Safety Systems PPS (LSS&RSS), EPS
- Training and User Interactions
- Collaborative Research approach with established research groups

# Laser plasma accelerators are being developed for future colliders and ultrafast radiation sources



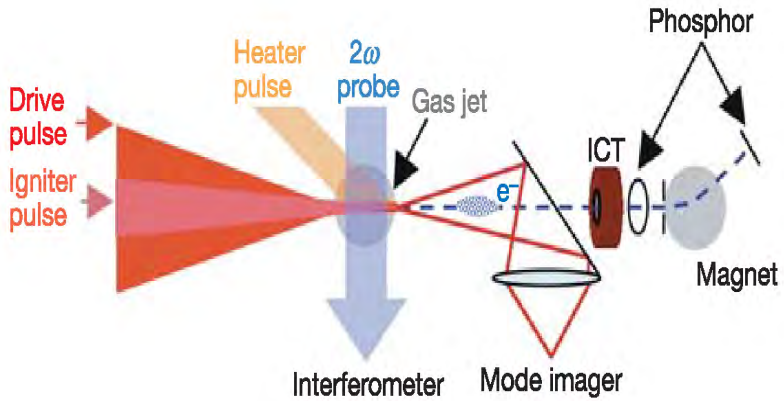



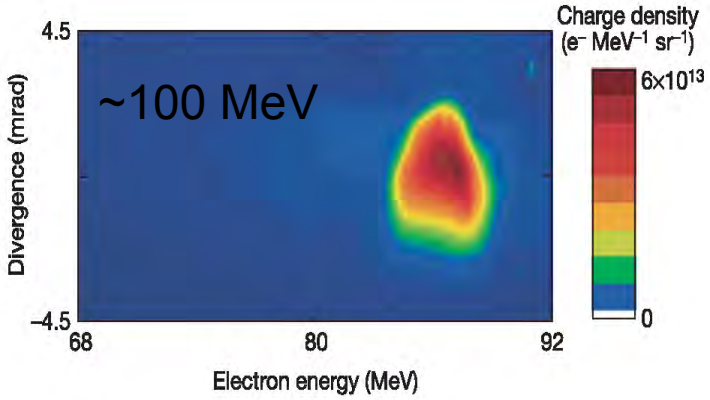



# Channel guided laser plasma accelerators have produced up to GeV beams from cm-scale structures

## 2004 result: 10 TW laser, mm-scale plasma

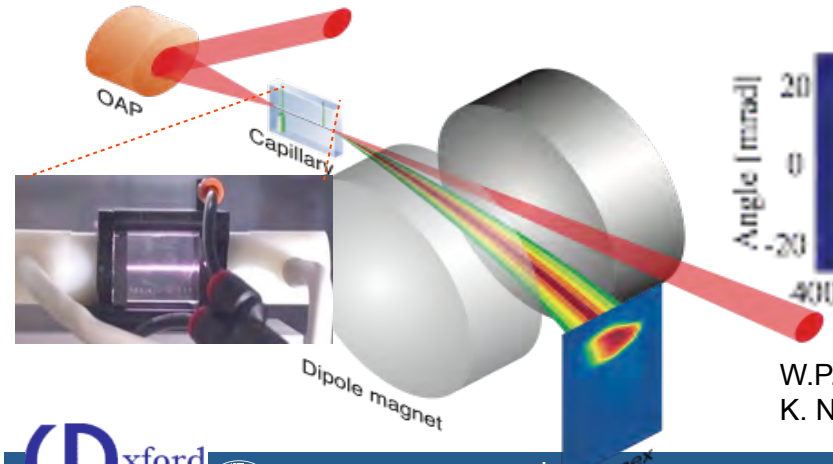




C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

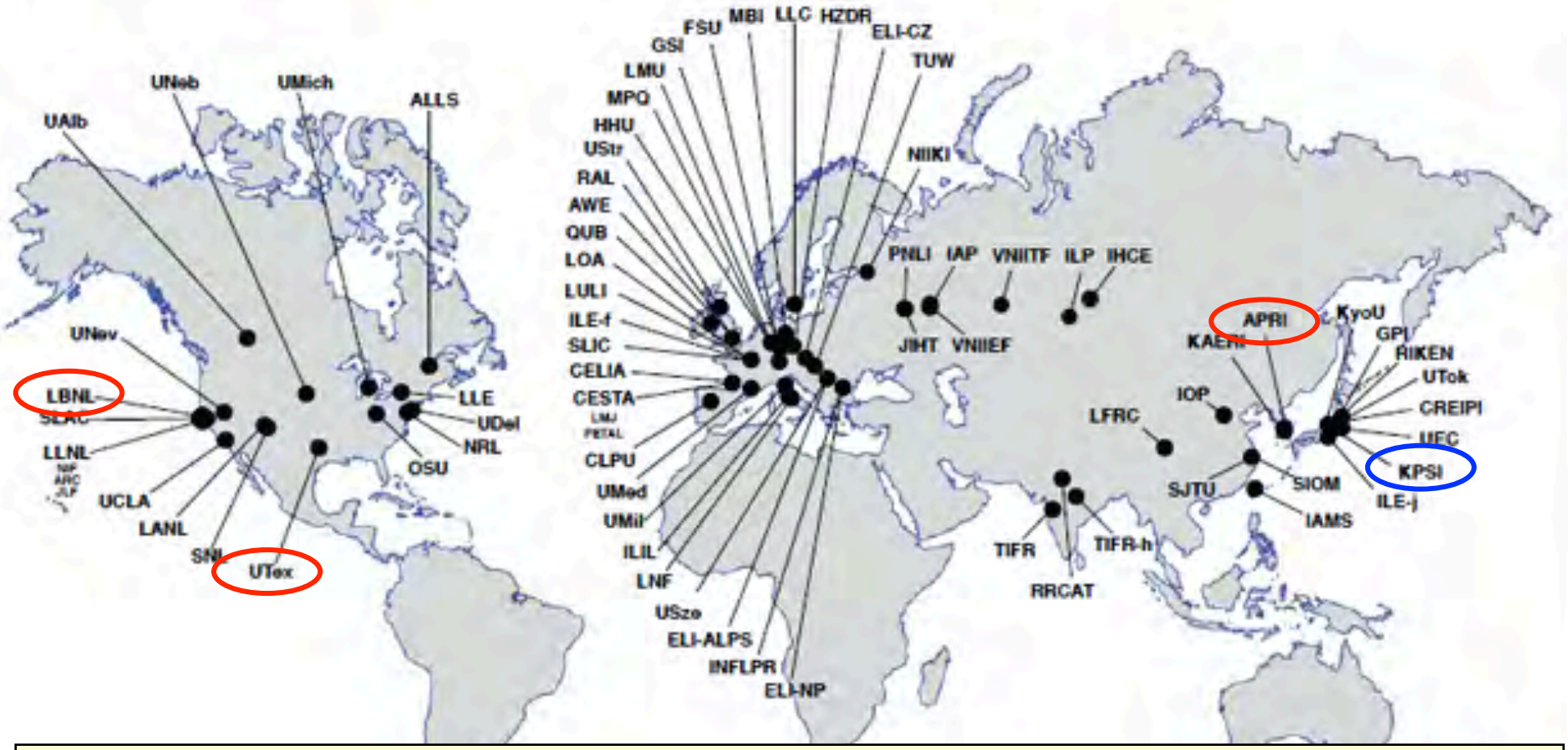
## 2006 result: 40 TW laser, cm-scale plasma






W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)
K. Nakamura et al., Phys. Plasmas **14,** 056708 (2007)

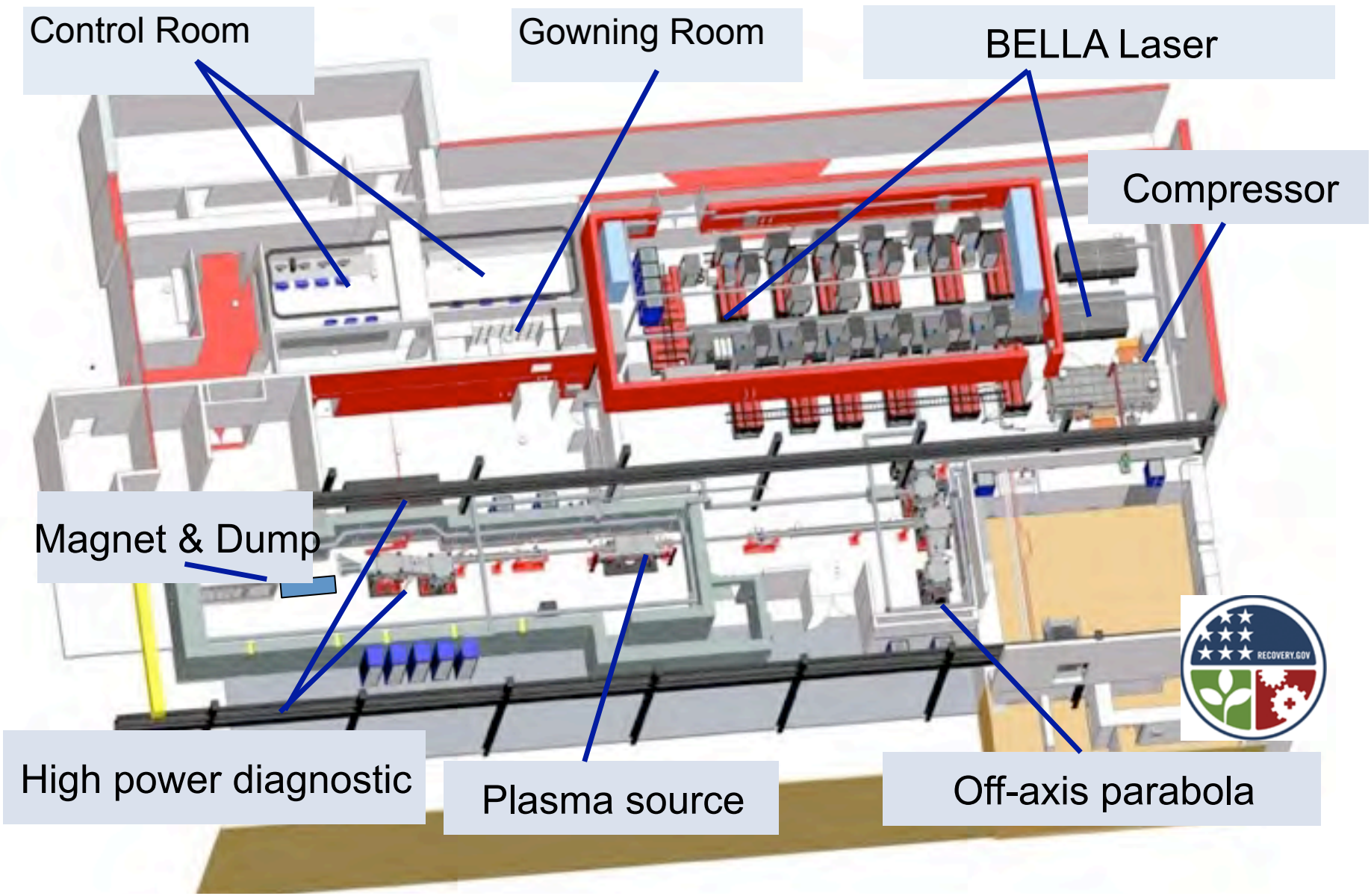
# Petawatt class lasers becoming available with a ten-fold expansion planned by 2017-2018




- Total peak power of all CPA systems operating today is ~11.5 PW
- By 2018 planned CPA projects will bring total to ~ 127 PW
- Estimates do not include present MJ or planned Exawatt scale projects

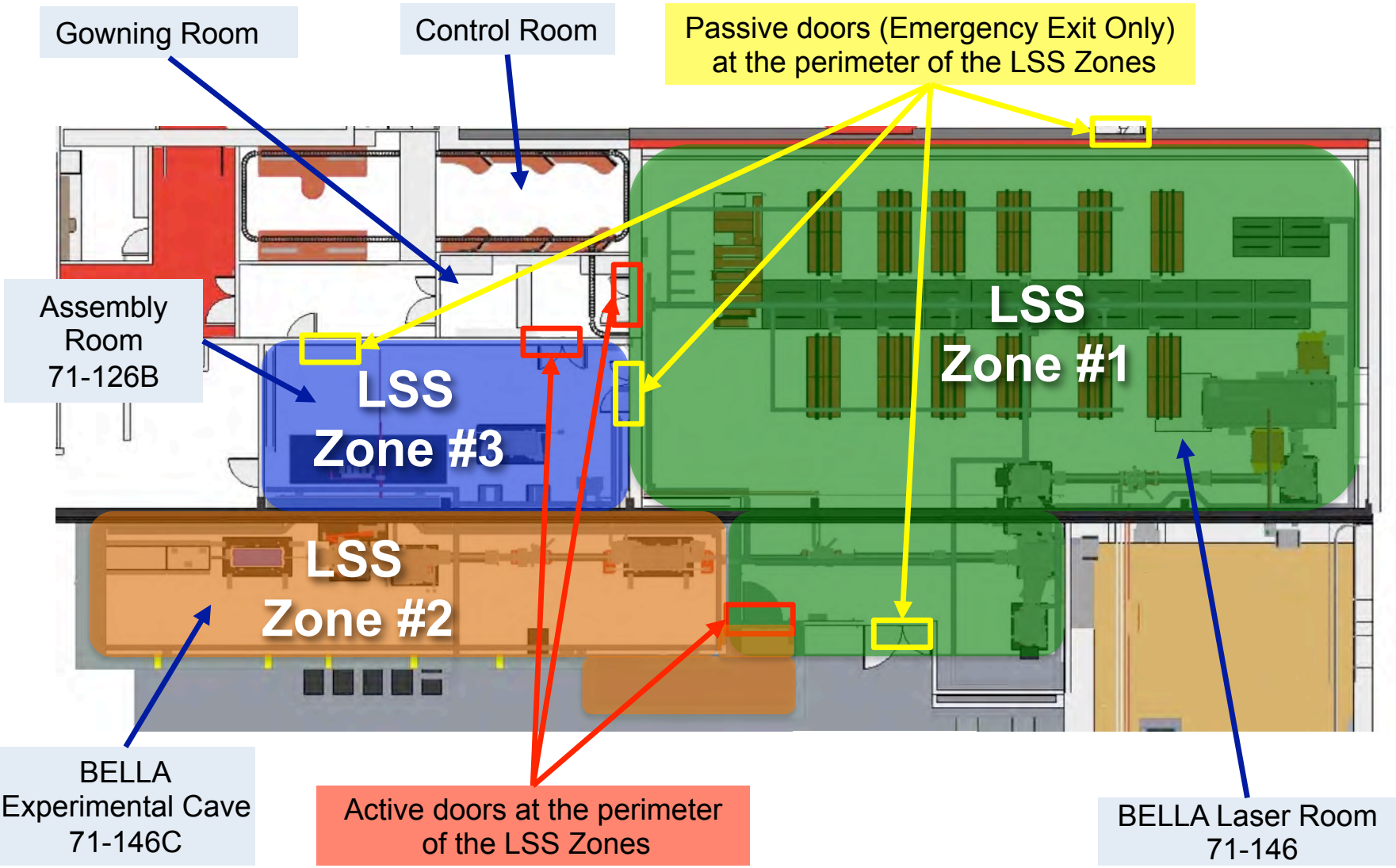
Courtesy: Chris Barty, LLNL

# The BELLA facility houses a state-of-the-art PW-laser for laser plasma accelerator (LPA) science



# The BELLA PW Laser System at LBNL

# The BELLA PW Laser Interlock Zones were developed to efficiently mitigate laser and radiation hazard



# Targeted Review Process

The PPS was reviewed in a targeted approach

The purpose of a targeted review process is to increase the number of hours spent analyzing a system by breaking the system into manageable study elements

The reviews were parsed to provide a targeted study of each of the PPS elements

- Requirements
- Software
- Hardware
- Quality Assurance testing

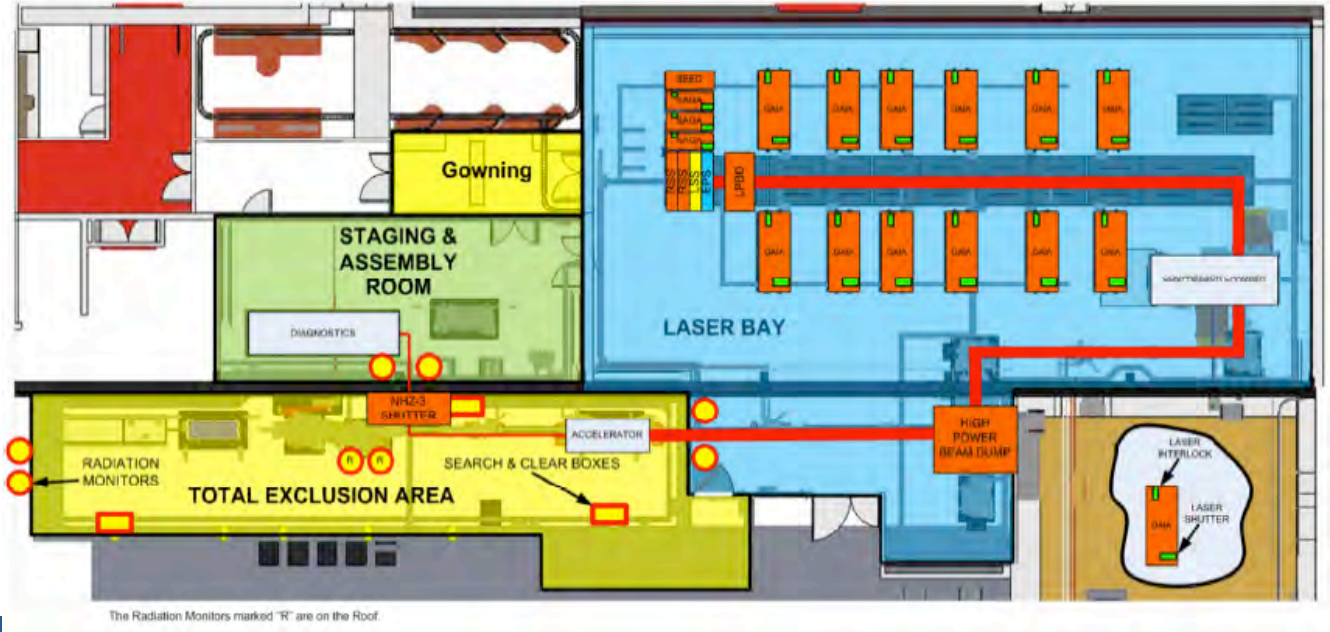
Each review was staffed with a small group of highly qualified personnel

# Personnel Protection System (LSS & RSS)

PPS is a redundant interlock system that prevents entering TEA when beam is delivered

Consists of: Interlock access door position sensing devices, key control panels, the relay logic devices and the diagnostics displays associated with each component of the PPS safety systems.

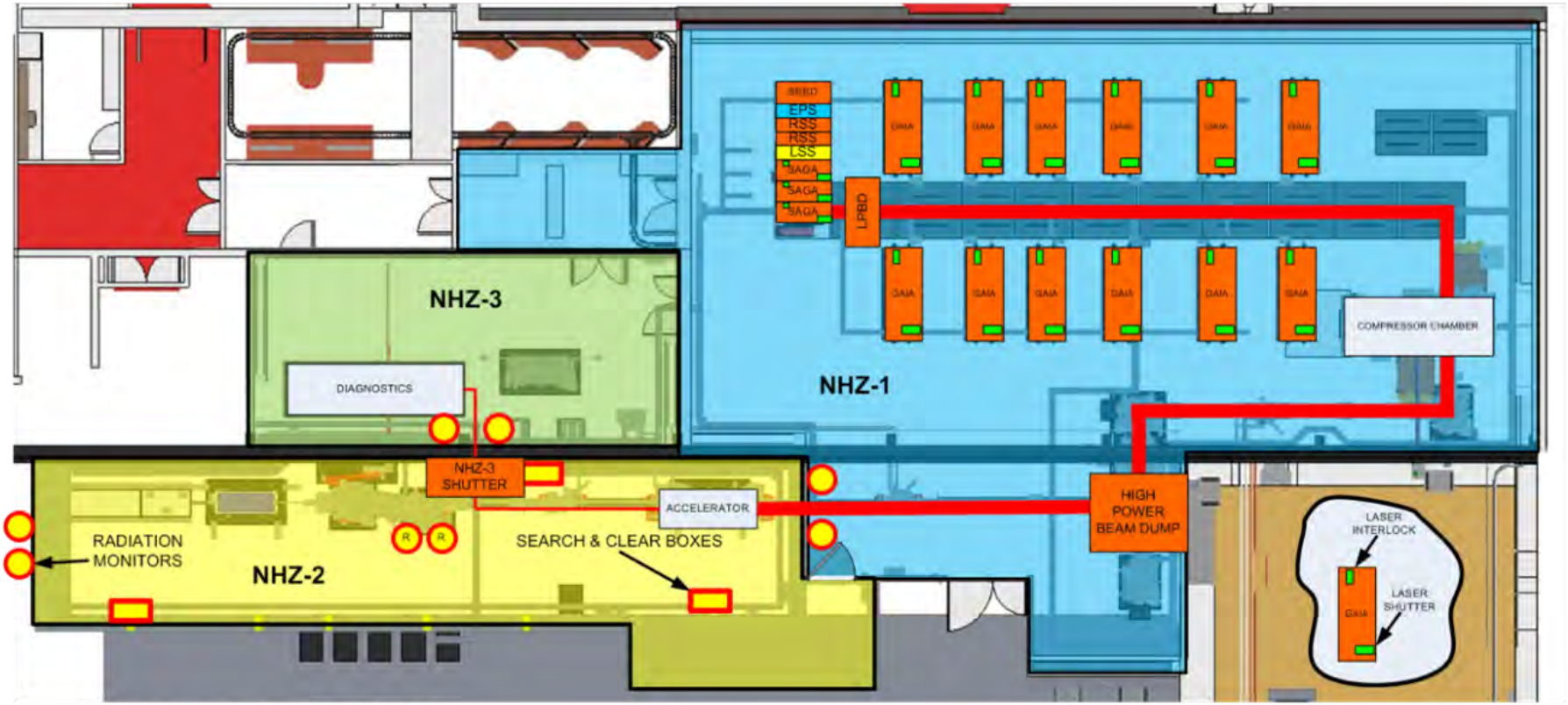
If one or any component fails the interlock system will disable the laser plasma accelerator system



# PPS → LSS

The LSS is divided into 3 Nominal Hazard Zones (NHZ)

Each zone has specific requirements for allowing laser operation within the zone.

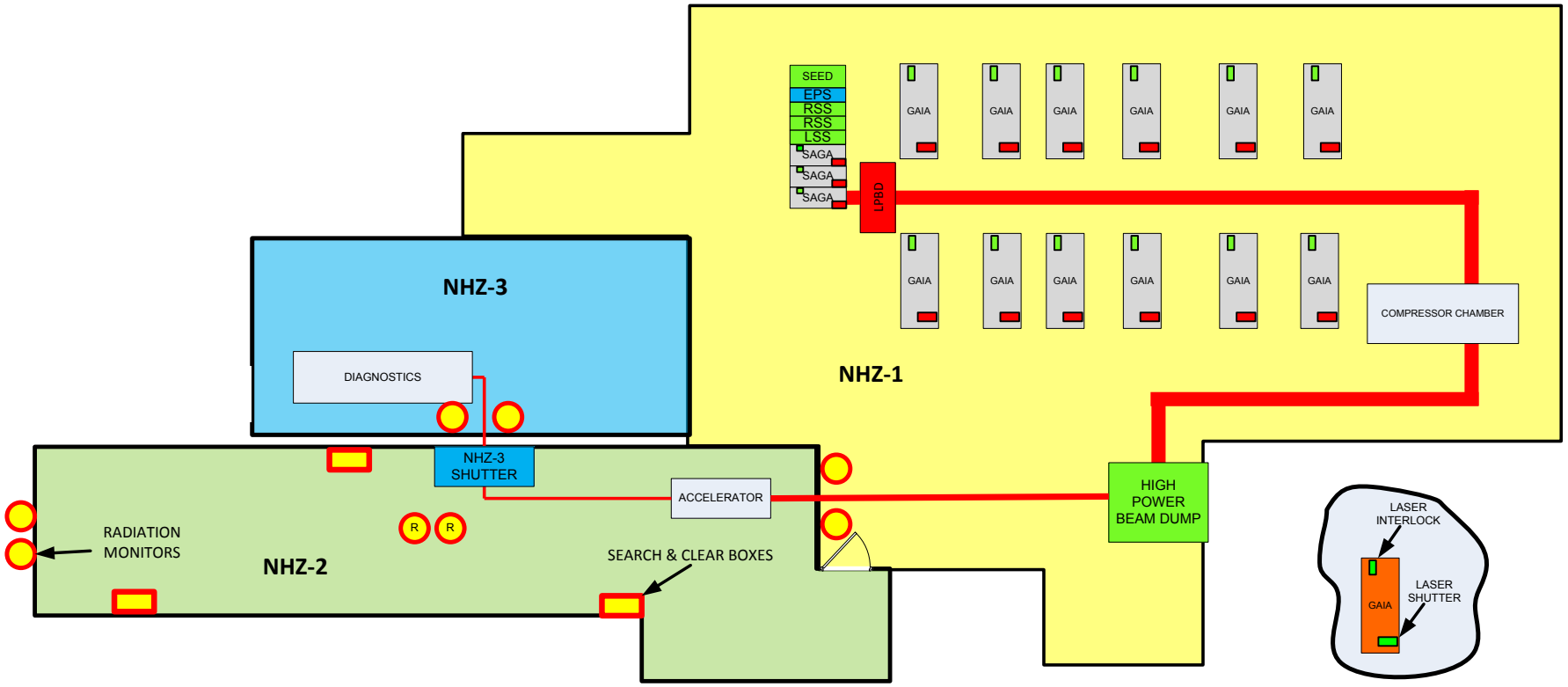



The Radiation Monitors marked "R" are on the Roof.

# Alignment Mode

SAGA and GAIA laser shutters closed for low power laser alignment

**PPS → RSS: Five modes**
- Safe Mode
- Diagnostic Mode
- **Alignment Mode**
- High-E Mode
- Crash (Emergency Off State)

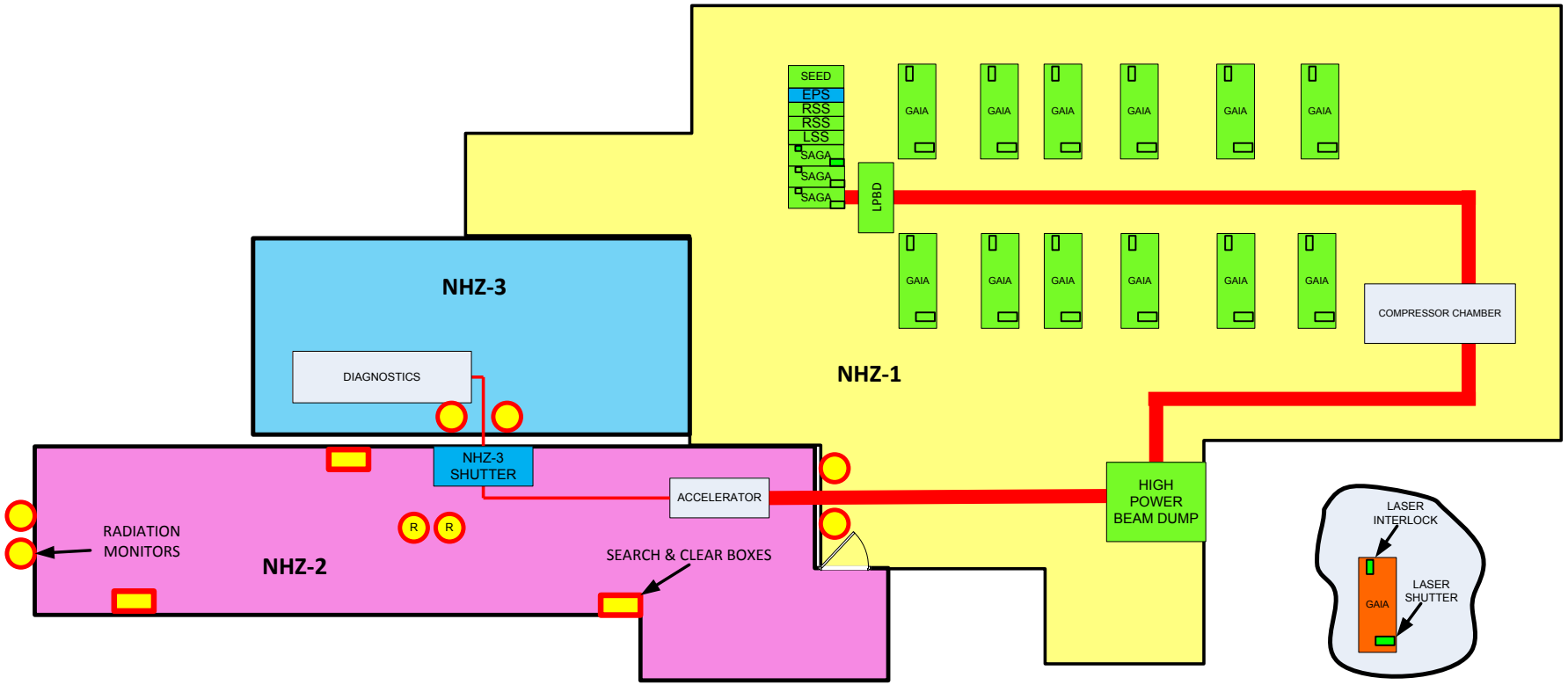



The Radiation Monitors marked "R" are on the Roof.

# High-E Mode

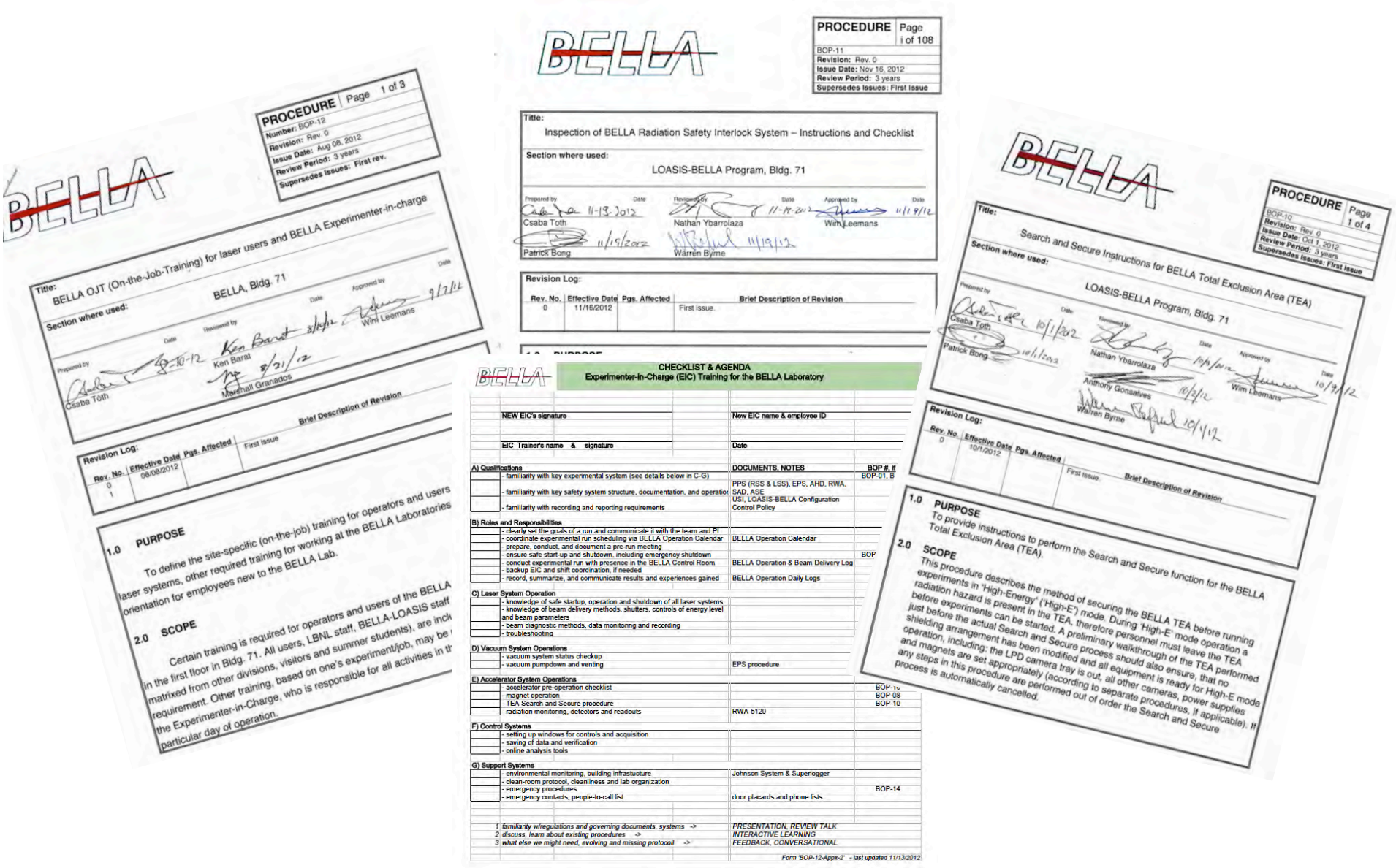
Enclosure Searched & Secure for normal high power laser operation w/targets

**PPS → RSS: Five modes**
- Safe Mode
- Diagnostic Mode
- Alignment Mode
- **High-E Mode**
- Crash (Emergency Off State)




The Radiation Monitors marked "R" are on the Roof.

# BELLA Procedures Control On-the-Job-Training (OJT), Interlock Testing and 'Search & Clear' Protocol



BELLA

PROCEDURE | Page i of 108
BOP-11
Revision: Rev. 0
Issue Date: Nov 16, 2012
Review Period: 3 years
Supersedes Issues: First issue

Title: Inspection of BELLA Radiation Safety Interlock System – Instructions and Checklist
Section where used: LOASIS-BELLA Program, Bldg. 71
Prepared by: Csaba Toth 11-13-2012 | Reviewed by: Nathan Ybarrolaza 11-14-2012 | Approved by: Wim Leemans 11/19/12
Patrick Bong 11/15/2012 | Warren Byrne 11/19/12

Revision Log:

| Rev. No. | Effective Date | Pgs. Affected | Brief Description of Revision |
|---|---|---|---|
| 0 | 11/16/2012 | | First issue. |

PROCEDURE | Page 1 of 3
Number: BOP-12
Revision: Rev. 0
Issue Date: Aug 08, 2012
Review Period: 3 years
Supersedes Issues: First rev.

Title: BELLA OJT (On-the-Job-Training) for laser users and BELLA Experimenter-in-charge
Section where used: BELLA, Bldg. 71
Prepared by: Csaba Toth 8-10-12 | Reviewed by: Ken Barat 8/10/12 | Approved by: Wim Leemans 9/7/12
Marshall Granados 8/21/12

Revision Log:

| Rev. No. | Effective Date | Pgs. Affected | Brief Description of Revision |
|---|---|---|---|
| 0 | 08/08/2012 | | First issue |
| 1 | | | |

1.0 PURPOSE

To define the site-specific (on-the-job) training for operators and users laser systems, other required training for working at the BELLA Laboratories orientation for employees new to the BELLA Lab.

2.0 SCOPE

Certain training is required for operators and users of the BELLA in the first floor in Bldg. 71. All users, LBNL staff, BELLA-LOASIS staff matrixed from other divisions, visitors and summer students), are inclu requirement. Other training, based on one's experiment/job, may be r the Experimenter-in-Charge, who is responsible for all activities in th particular day of operation.

BELLA

CHECKLIST & AGENDA
Experimenter-in-Charge (EIC) Training for the BELLA Laboratory

NEW EIC's signature | New EIC name & employee ID
EIC Trainer's name & signature | Date

| | | | |
|---|---|---|---|
| A) Qualifications | | DOCUMENTS, NOTES | BOP #, if |
| | - familiarity with key experimental system (see details below in C-G) | | BOP-01, B |
| | - familiarity with key safety system structure, documentation, and operation | PPS (RSS & LSS), EPS, AHD, RWA, SAD, ASE | |
| | - familiarity with recording and reporting requirements | USI, LOASIS-BELLA Configuration Control Policy | |
| B) Roles and Responsibilities | | | |
| | - clearly set the goals of a run and communicate it with the team and PI | | |
| | - coordinate experimental run scheduling via BELLA Operation Calendar | BELLA Operation Calendar | |
| | - prepare, conduct, and document a pre-run meeting | | |
| | - ensure safe start-up and shutdown, including emergency shutdown | | BOP |
| | - conduct experimental run with presence in the BELLA Control Room | BELLA Operation & Beam Delivery Log | |
| | - backup EIC and shift coordination, if needed | | |
| | - record, summarize, and communicate results and experiences gained | BELLA Operation Daily Logs | |
| C) Laser System Operation | | | |
| | - knowledge of safe startup, operation and shutdown of all laser systems | | |
| | - knowledge of beam delivery methods, shutters, controls of energy level and beam parameters | | |
| | - beam diagnostic methods, data monitoring and recording | | |
| | - troubleshooting | | |
| D) Vacuum System Operations | | | |
| | - vacuum system status checkup | | |
| | - vacuum pumpdown and venting | EPS procedure | |
| E) Accelerator System Operations | | | |
| | - accelerator pre-operation checklist | | BOP-10 |
| | - magnet operation | | BOP-08 |
| | - TEA Search and Secure procedure | | BOP-10 |
| | - radiation monitoring, detectors and readouts | RWA-5129 | |
| F) Control Systems | | | |
| | - setting up windows for controls and acquisition | | |
| | - saving of data and verification | | |
| | - online analysis tools | | |
| G) Support Systems | | | |
| | - environmental monitoring, building infrastucture | Johnson System & Superlogger | |
| | - clean-room protocol, cleanliness and lab organization | | |
| | - emergency procedures | | BOP-14 |
| | - emergency contacts, people-to-call list | door placards and phone lists | |
| | 1 familiarity w/regulations and governing documents, systems -> | PRESENTATION, REVIEW TALK | |
| | 2 discuss, learn about existing procedures -> | INTERACTIVE LEARNING | |
| | 3 what else we might need, evolving and missing protocoll -> | FEEDBACK, CONVERSATIONAL | |

Form 'BOP-12-Appx-2' - last updated 11/13/2012

BELLA

PROCEDURE | Page 1 of 4
BOP-10
Revision: Rev. 0
Issue Date: Oct 1, 2012
Review Period: 3 years
Supersedes Issues: First issue

Title: Search and Secure Instructions for BELLA Total Exclusion Area (TEA)
Section where used: LOASIS-BELLA Program, Bldg. 71
Prepared by: Csaba Toth 10/1/2012 | Reviewed by: Nathan Ybarrolaza 10/1/2012 | Approved by: Wim Leemans 10/1/12
Patrick Bong 10/1/2012 | Anthony Gonsalves 10/2/12 | Warren Byrne 10/4/12

Revision Log:

| Rev. No. | Effective Date | Pgs. Affected | Brief Description of Revision |
|---|---|---|---|
| 0 | 10/1/2012 | | First issue. |

1.0 PURPOSE

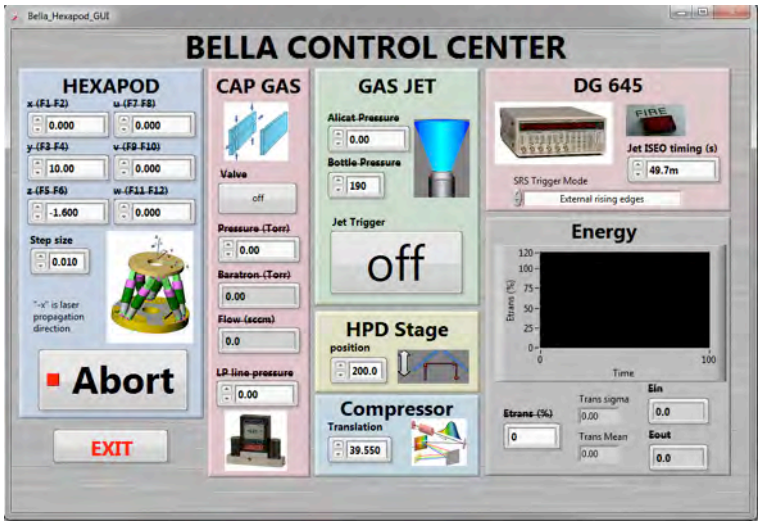
To provide instructions to perform the Search and Secure function for the BELLA Total Exclusion Area (TEA).

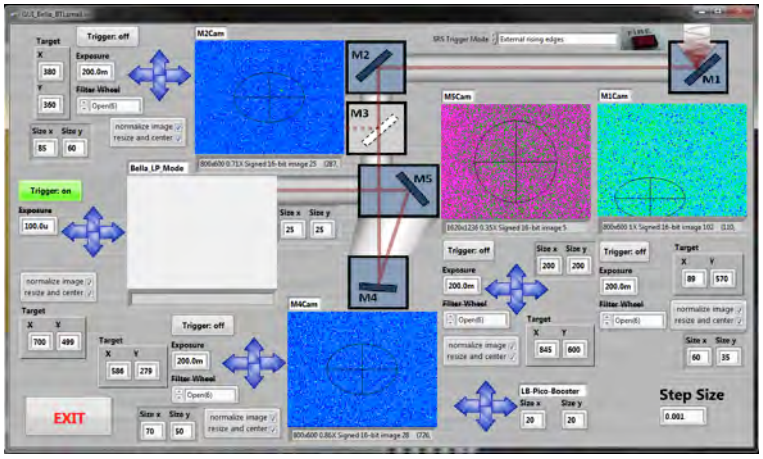
2.0 SCOPE

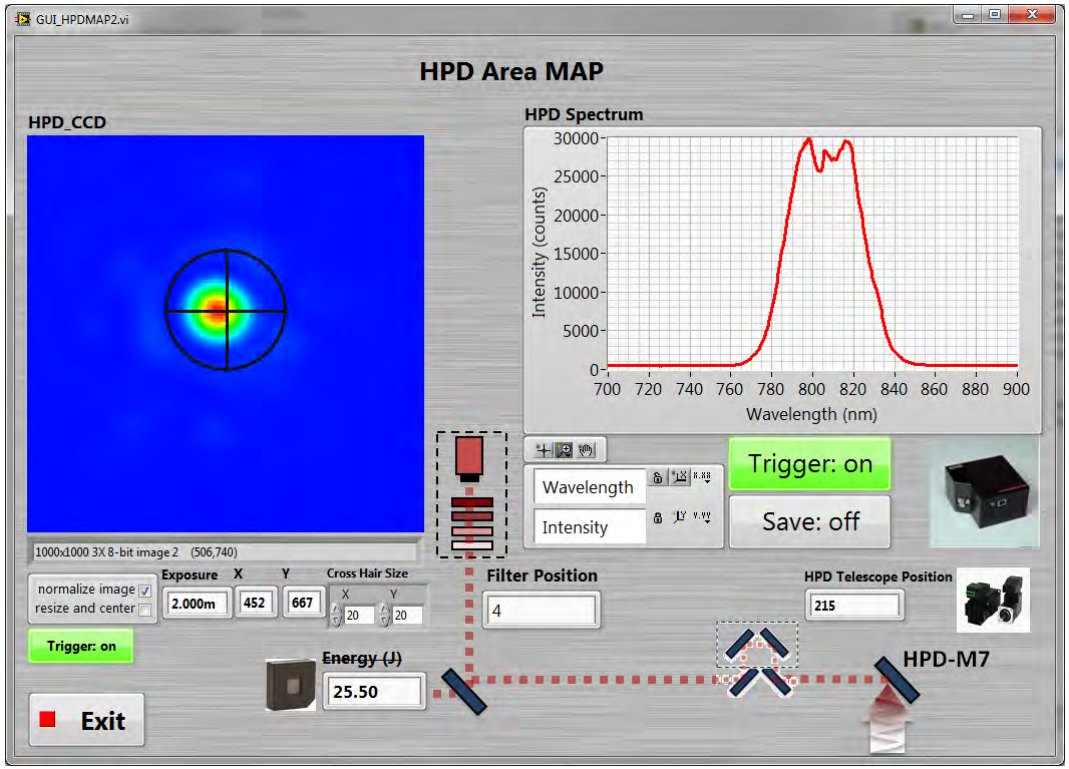
This procedure describes the method of securing the BELLA TEA before running experiments in 'High-Energy' ('High-E') mode. During 'High-E' mode operation a radiation hazard is present in the TEA, therefore personnel must leave the TEA before experiments can be started. A preliminary walkthrough of the TEA performed just before the actual Search and Secure process should also ensure, that no shielding arrangement has been modified and all equipment is ready for High-E mode operation, including: the LPD camera tray is out, all other cameras, power supplies and magnets are set appropriately (according to separate procedures, if applicable). If any steps in this procedure are performed out of order the Search and Secure process is automatically cancelled.

# A LabView-based experiment control and data acquisition system has been developed for easy maintenance and flexibility

## Complex GUIs communicating with many devices are simple and quick to write



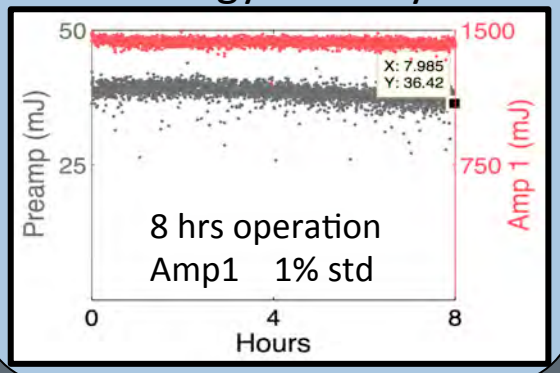



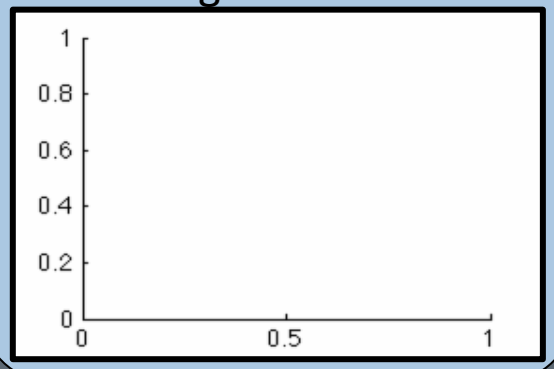
# BELLA delivered ~40 fs pulses with 1e-8 contrast & ~0.9 Strehl ratio for the first e-beam campaigns, then upgraded toward cleaner and shape-controllable ~30 fs pulses with 1e-10 contrast

## BELLA Laser Quality

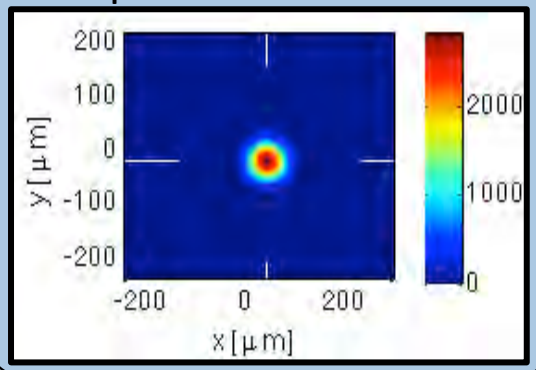
### Energy Stability



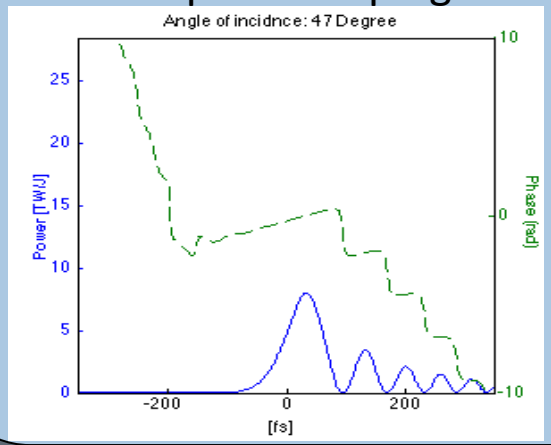

### Pointing: 1.2 urad rms



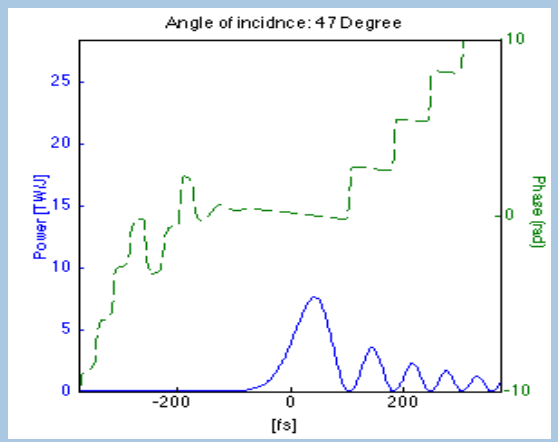

### Spatial: Strehl ~0.9



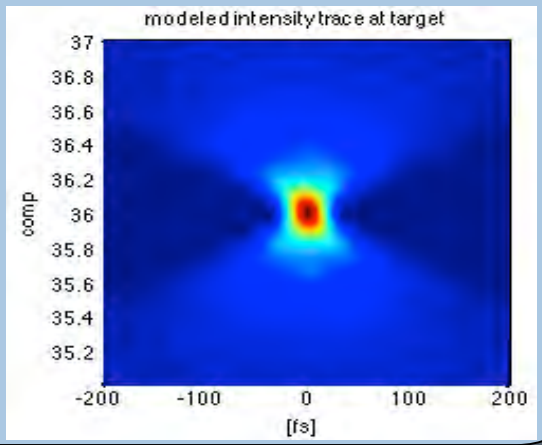

### Temporal Shaping



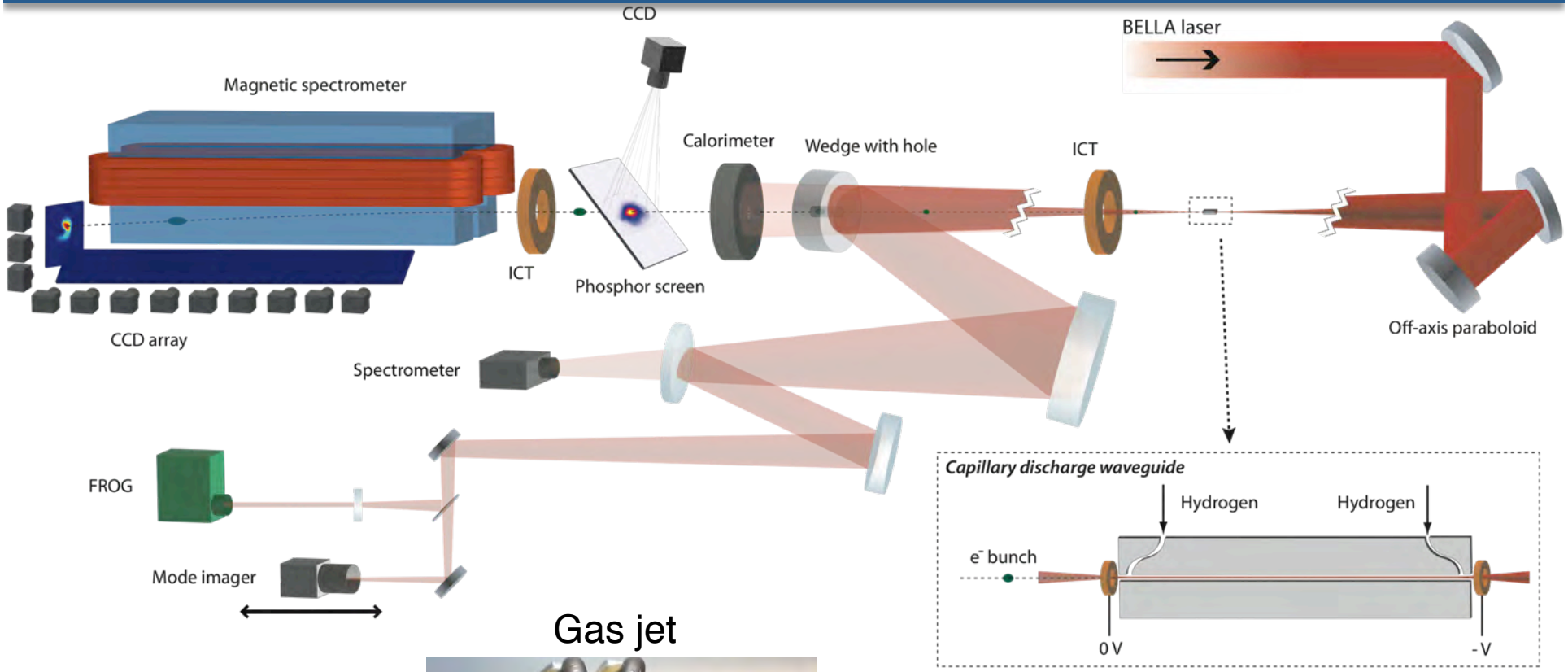

### Toward Fourier limit



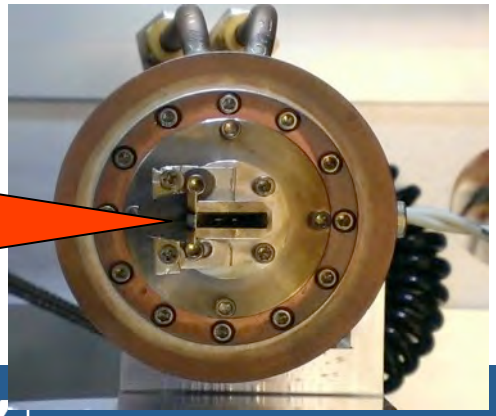

### = Smooth structure



# Experiments at LBNL use the BELLA laser focused by a 13.5 m focal length off-axis paraboloid onto gas jet or capillary discharge targets



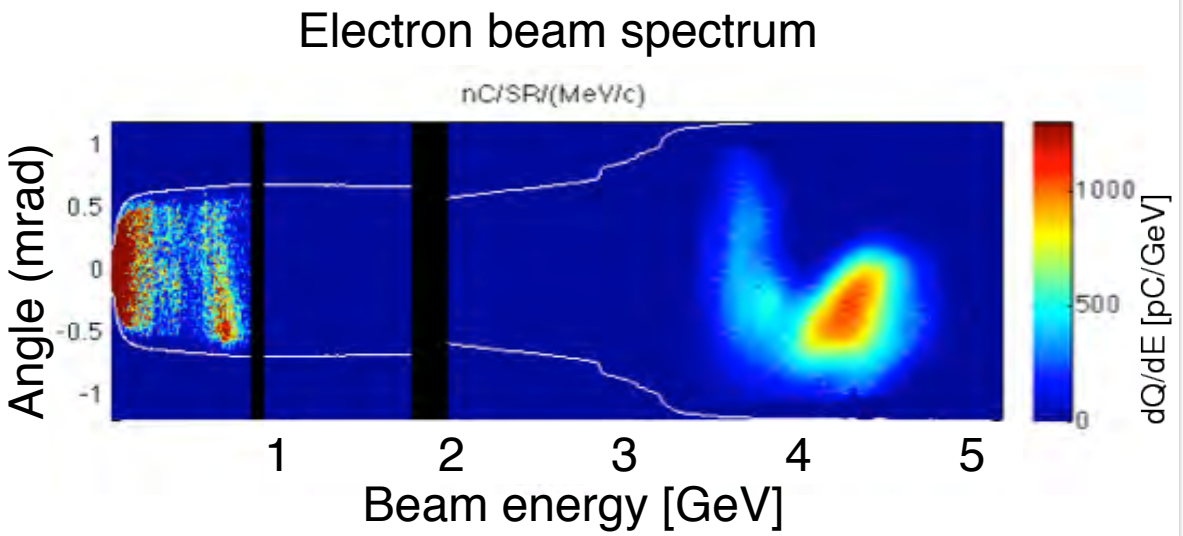

Gas jet

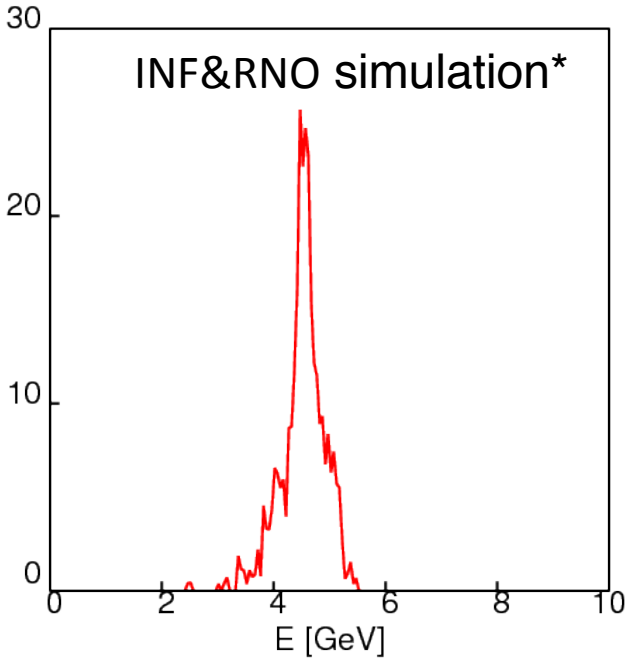



Capillary discharge

# 4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J on target)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012




- **Laser** (E=15 J):
  - Measured longitudinal profile ($T_0$= 40 fs)
  - Measured far field mode ($w_0$=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, $n_0$~6x$10^{17}$ $cm^{-3}$)

| | Exp. | Sim. |
|---|---|---|
| Energy | 4.25 GeV | 4.5 GeV |
| ΔE/E | 5% | 3.2% |
| Charge | ~20 pC | 23 pC |
| Divergence | 0.3 mrad | 0.6 mrad |

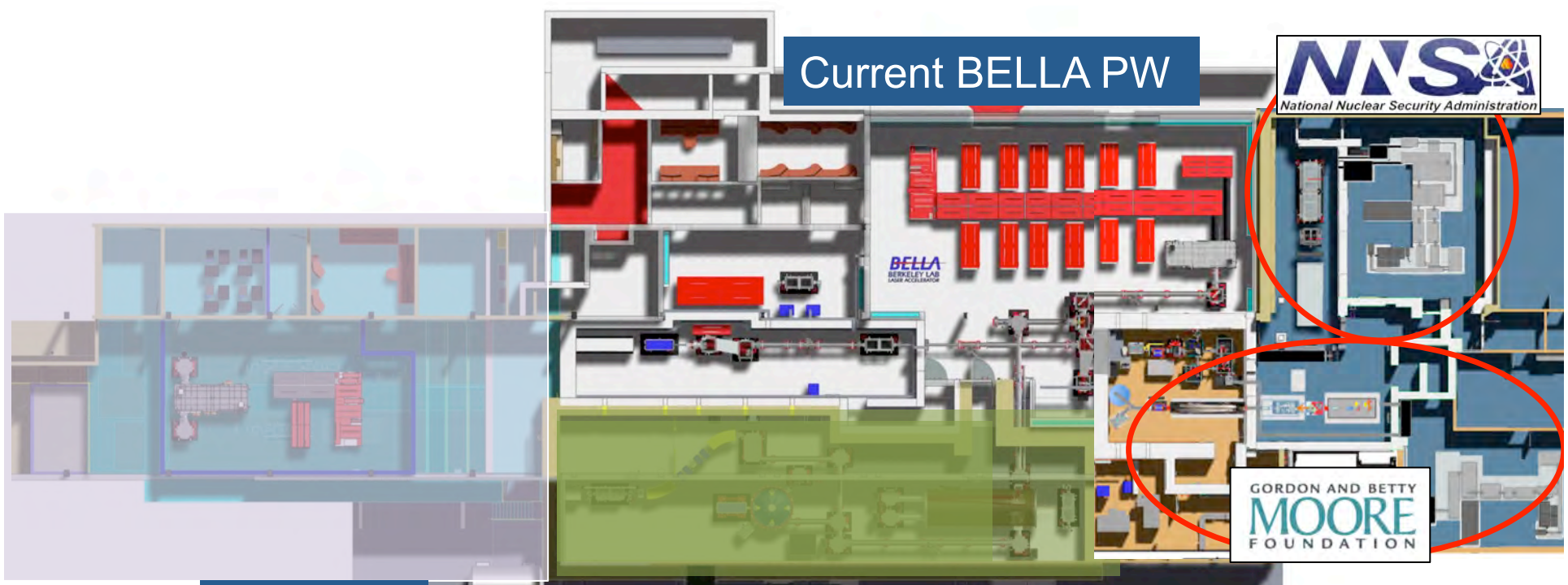

*W.P. Leemans et al., Phys. Rev. Lett.* ***113****, 245002 (2014)*

*A.J. Gonsalves et al., Phys. Plasmas,* ***22****, 056703 (2015)*

# Operations & Challenges Summary

- PW-class lasers are enabling multi-GeV laser plasma accelerator research
- Experiments with gas jet, gas cell, and capillary discharges:
  - Laser spatial, temporal, and amplitude stabilities have important impact on performance and results achievable
- Preparation for the transition to become a Collaborative Research Facility:
  - Collect and analyze lessons learned (both internal and national, e.g. Texas PW)
  - Maintain & develop further the On-the-Job Training (OJT) structure
  - Optimal use of the new Work Planning and Control (WPC) system of LBNL
  - Effectively rely on the other 5 existing National User Facilities of LBNL:
    - Advanced Light Source - ALS
    - Molecular Foundry
    - Joint Genome Institute - JGI
    - NERSC
    - ESnet

# BELLA Facility is designed for laser plasma accelerator R&D and expanding toward ultra-high intensity laser-matter experiments




k-BELLA (initiative)

BELLA-i beamline (Initiative)

Gamma-rays, FELs, medical apps

# BELLA-i - a facility for high energy density physics and discovery plasma science at Berkeley Lab

| BELLA-i | 1 | 2 | 3 |
|---|---|---|---|
| peak intensity ($W/cm^2$) | $2 \times 10^{19}$ | $3 \times 10^{21}$ | $3 \times 10^{21}$ |
| pulse length | 30 fs | 30 fs | 30 fs |
| peak pulse energy | 40 J | 40 J | 40 J |
| laser spot size | 55 μm | 5 μm | 5 μm |
| peak repetition rate | 1 Hz* | 1 Hz* | 1 Hz |
| contrast (ns) | $10^{-10}$ | $10^{-10}$ | $>10^{-14}$ |
| diagnostics (details to be determined) | • optical spectrometers<br>• ion and electron spectrometers<br>• … | • optical pump- probe<br>• betatron x-rays<br>• MeV protons<br>• … | • same as 2<br>• beamline for experiments with laser accelerated ions<br>• … |
| 1st access (estimates) | 2017-2018 | 2018-2019 | 2019-2020 |

1. Experiments with the existing, long focal length BELLA beamline in the existing cave
2. Experiments in the existing BELLA cave with a new dual-beam line
   - * shielding in the BELLA cave limits the repetition rate for experiments with generation of intense pulses of >20 MeV protons
3. Experiments in a new cave with a beam line for laser accelerated ions
   - * improved shielding in a three-times larger experimental area for continuous operation at 1 Hz

# Summary & Outlook

**Co-location and unified operation structure of other LPA beamlines based on multi-TW CPA lasers at the BELLA Center help to establish coherent measurement standards and efficient training ground**

- gamma production w/upgraded LOASIS setup (NNSA/DNN funds – construction in progress)
- undulator beamline for FEL (Gordon & Betty MOORE foundation – construction in progress)
- k-BELLA: high repetition rate laser development for high average power LPAs (pilot program is running)

# Summary & Outlook

**Upcoming experiments and near-future plans w/the BELLA PW laser at the BELLA Center pave the road toward a Collaborative Research Facility devoted to Laser Plasma Acceleration (LPA) science**

- solid targets in the current BELLA PW configuration (planning in progress)
- split BELLA PW beam for BELLA staging, 5+5 GeV electrons (planning in progress)
- BELLA-i (new caves, new focusing arrangement, future implementation) for ion acceleration

# BELLA Center staff (FY ’15 - ’16)

***Scientific Staff:***


Wim Leemans


Eric Esarey


Csaba Toth


Cameron Geddes


Carl Schroeder


Jean-Luc Vay


Anthony Gonsalves


Jeroen van Tilborg


Kei Nakamura


Carlo Benedetti


Stepan Bulanov


Sven Steinke

***Guest Researchers & PostDocs:***

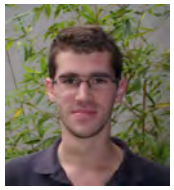
Andy Roberts

Feng Liu

Sergei Rykovanov

Alexandre Bonatto

***Postdoctoral Scholars:***


Remi Lehe

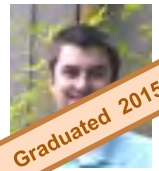

Henri Vincenti


Hann-Shin Mao

***PhD, Masters, undergrad students:*** **Names in blue are at U.C. Berkeley**


Joost Daniels


Daniel Mittelberg

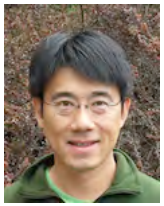


Brian Shaw


Chris Pieronek


Kelly Swanson

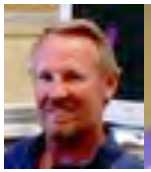

Fumika Isono


Hai-En Tsai


Sam Barber

New PhD student from spring 2016: Blagoje Djordevic

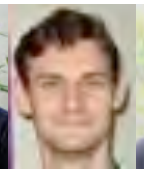
***Engineering & Technical Support:***

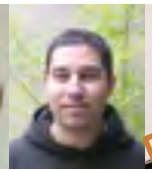

Don Syversrud


Dave Evans

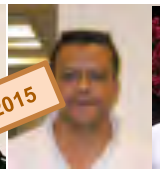

Mark Kirkpatrick

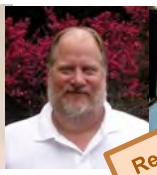

Tyler Sipla

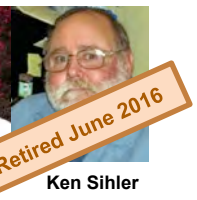

Nathan Ybarrolaza


Greg Mannino

Aalhad Deshmukh

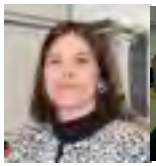

Art Magana

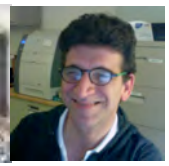

Joe Rile



Ken Sihler

***Administrative Support:***


Martha Condon


Wes Tabler